

Disks around massive young stellar objects: are they common?

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ABSTRACT

We present K-band polarimetric images of several massive young stellar objects at resolutions $\sim 0.1\text{--}0.5$ arcsec. The polarization vectors around these sources are nearly centro-symmetric, indicating they are dominating the illumination of each field. Three out of the four sources show elongated low-polarization structures passing through the centers, suggesting the presence of polarization disks. These structures and their surrounding reflection nebulae make up bipolar outflow/disk systems, supporting the collapse/accretion scenario as their low-mass siblings. In particular, S140 IRS1 show well defined outflow cavity walls and a polarization disk which matches the direction of previously observed equatorial disk wind, thus confirming the polarization disk is actually the circumstellar disk. To date, a dozen massive protostellar objects show evidence for the existence of disks; our work add additional samples around MYSOs equivalent to early B-type stars.

Subject headings: stars:formation—stars:circumstellar matter—ISM:reflection nebulae

1. Introduction

With the wide availability of sub-arcsec observations, the presence of disks around massive young stellar objects (MYSOs) has become a hot topic recently. The reason for this, is the dispute about the way how massive stars are formed. That massive stars are formed in a scaled-up version of how low-mass stars form (Shu, Adams, & Lizano 1987) would be a natural thought. However, it has been proposed that, if the mass of the central star exceeds $8 M_{\odot}$, the tremendous radiation pressure from the central star will halt the mass accretion and keep it from growing (e.g., Kahn 1974; Palla & Stahler 1993). Such a consideration leads to an entirely different mechanism, i.e., massive stars may be formed through mergers of lower-mass protostars (Bonnell, Bate & Zinnecker 1998). On the other hand, a number of solutions have been proposed to account for the radiation pressure problem, such as non-isotropic accretion (Yorke & Sonnhalter 2002), different dust opacity (Kahn 1974), and redirection of radiation by disk/outflow system (Krumholz, McKee, & Klein

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2005). The presence of disk/outflow system around MYSOs will provide key evidence to evaluate these two kind of scenarios.

Disks around MYSOs have been detected over a wide range of wavelengths with different tracers (Patel et al. 2005; Jiang et al. 2005; Cesaroni et al. 2006; Beltrán et al. 2006). These results suggest that up to early B type stars **can** be formed through a similar route as solar type stars. In this work we report sub-arcsec near-infrared (NIR) polarimetric imaging observations which show three polarization disks that can be best interpreted as disks or toroids around the MYSOs.

2. Observations and data reduction

S140 IRS1 was observed on 2005 June 28, and the other three were observed on 2006 November 5, all with the Coronagraphic Imager with Adaptive Optics (CIAO, Tamura et al. 2000) mounted on the Subaru telescope. The polarization mode was set on (Tamura et al. 2003) by placing a rotatable half-wave plate (images taken at waveplate angles of 0, 22.5, 45 and 67.5 degrees), upstream of the adaptive optics (AO) system, and a cooled wiregrid polarizer inside the CIAO cryostat. For each waveplate angle, the exposure times were 5 min for S140 IRS1, 4 min for S255 IRS1, 2 min for NGC7538 IRS1 and 6 min for IRAS23033+5951, respectively. The nights were clear and seeing was stable so that the point spread function of the optical system did not change much. For S140 IRS1, AO was not used due to a technical problem, resulting in a natural seeing, i.e., $\sim 0.45''$ (FWHM); for the other targets, the AO system was applied, delivering a resolution of $0.15''$ to $0.2''$. The pixel size was set to $0.021''$ for all the observations.

The images were reduced in the standard way with IRAF packages, as described in Jiang et al. (2005). The polarization data of S140 IRS1 were calibrated with AFGL 2591 (Tamura et al. 1991); whilst the others were calibrated with NGC 7538 IRS1 (Yao & Sato 1999). Two schemes were applied to calculate the zero-angle correction of polarization. One is to measure the polarization of the point sources of calibration, with the same aperture as done in Tamura et al. (1991) and Yao & Sato (1999). The other is to calculate the centroid of the polarization pattern of the assumed reflection areas. By adjusting the zero-angle correction, we can align the centroid to the center of the assumed illuminating source. In both schemes, the zero-angle correction agreed within one degree. Meanwhile, the assumption of centro-symmetric polarization pattern around NGC 7538 IRS1 can be tested by checking the non-calibrated polarization angles, which are roughly equal in every radiating line from the object. The polarization degrees were not calibrated because we used relative flux to calculate them. The instrumental polarization is negligible (less than 1%), and the polarization efficiency at K-band is about 97%.

3. Results

The main results are shown in Fig. 1. A common feature is noticed from inspection of the polarization vectors (left panels) for each field. In most of the fields, the polarization vectors are circling around the center, forming centro-symmetric patterns, suggesting the MYSOs are dominating the illumination of some or all of the fields. However, details of the polarization morphology are different from region to region, and are described below.

S140 IRS1: The polarization vectors are perfectly centro-symmetric (Fig. 1a, left panel), suggesting that the source is dominating its surrounding area; no other sources affect the polarization. Two low-

polarization lanes pass through the central source. One is in the southwest-northeast at a position angle (p.a., measured east of north) $\sim 45^\circ$, which is rather straight and narrow; the other is wider and a little curved to the north, and virtually perpendicular to the first one. In the pseudocolor image composed from intensity image and polarized flux image (Fig. 1a, right panel), two parabolically curved features, separated by the southwest-northeast lane, presumably representing reflection nebulosities, are seen opening towards the southeast and northwest, respectively. These two reflection nebulosities is probably the outflow cavity walls. A scattered photon is effectively polarized if the scattering angle (the angle between the incident and emerging direction) is near 90° (e.g., Code & Whitney 1995). This is why we can only see the polarized light on two sides of the wall, while little polarization is observed in between. It is particularly true for large opening angles, as in the case of S140 IRS1. The wall profile to the northwest is more clearly observable, because it delineates a red-shifted outflow lobe (Hayashi et al. 1987; Minchin, White & Padman 1993), where extinction is larger so that we can only see the most efficiently polarized light on the two sides. The blue-shifted outflow to the southeast shows much brighter reflection nebulosity, consistent with the result from the NIR speckle-interferogram images (Schertl et al. 2000; Weigelt et al. 2002). The asymmetry of the brightness between the nebulae, which had also been observed in CO lines (Hayashi et al. 1987), is probably a result of dust distribution around this object. The morphologies of the walls indicate that the opening angle is rather large ($\sim 150^\circ$), consistent with the poor outflow collimation ratio (Hayashi et al. 1987).

The low-polarization lane in the southwest-northeast, therefore, represents a polarization disk (PD). Such a kind of feature is observed in intermediate-mass young stars (Perrin et al. 2004) as well as in low- and high-mass protostars (Lucas et al. 2004; Jiang et al. 2005). Hoare (2006) observed IRS1 in the centimeter continuum band, and found an elongated structure, which is interpreted as an equatorial disk wind. An over-plot of the ionized disk wind on the pseudocolor image shows that the directions of the PD and the disk wind matches each other (Fig. 1a, right panel). This evidence strongly suggests that the PD is actually a physical disk. The diameter of the PD is rather large (≥ 2700 AU), implying the dusty disk is more extended than the ionized disk wind. Based on the bow-shock-like structures in the K'-band image, Weigelt et al. (2002) proposed a quadrupolar outflow scenario for IRS1 (see also Yao et al. 1998). However, since VLA4 is located along the path that the bow-shocks trace (Fig. 2, Weigelt et al. 2002), it is also possible that the 20° outflow is driven by VLA4. Given the configuration of the system we observed, a single bipolar outflow/disk system for IRS1 is more likely than multiple outflows.

S255 IRS1: A bipolar nebula is located around S255 IRS1 (Fig. 1b, right panel) at p.a. $\sim 35^\circ$. High degrees of polarization (up to $\sim 30\%$) in the nebula indicate that it should be a reflection nebula illuminated by the central source, IRS1, as illustrated by the polarization vectors (Fig. 1b, left panel). In the southwest part of the nebula there could be some contaminations—the outflow from IRS3 may overlap (Tamura et al. 1991). Still farther to the south ($\sim 3''$ from IRS1), a bright nebula is seen with scattering dominated by IRS3. In spite of this, the morphology of the bipolar nebula suggests an outflow from IRS1 with a small opening angle ($\leq 50^\circ$). Additional evidence is the H_2 emission knots (S255:H2 2, Miralles et al. 1997), which is located along the extension of the southern nebula (p.a. $\sim 220^\circ$), and which has been suggested to be excited by IRS1. The nebula is a little twisted in “S” shape, suggesting that it is a precessing outflow.

A biconical low-polarization lane runs through IRS1, roughly perpendicular to the axis of the reflection nebula at p.a. $\sim 110^\circ$, with a length of ~ 5700 AU. In Fig 1b (right panel) we indicate the shape of the structure between two curves. The polarization vectors there are roughly parallel to the lane, but the whole pattern of vectors is approximately elliptical. This structure is typically a PD, which has been well modelled (e.g., Bastien & Menard 1988) and observed in many cases (e.g., Whitney, Kenyon & Gomez 1997). It

usually suggests a disk or a toroid around the central source.

NGC7538 IRS1: Bright nebulosities are seen to the north and northeast of IRS1, but rather faint to the SE (Fig. 1c, right panel). The polarization degrees to the north (up to 30%) are higher than to the south ($\sim 10\%$), and the polarized flux there show irregular structures. The polarization pattern of these nebulosities is generally centro-symmetric with respect to IRS1 (Fig. 1c, left panel). This confirms the suggestion by Kraus et al. (2006) that the bright patches to the northwest are illuminated by IRS1. Within $\sim 1''$ of IRS1, the polarization degrees are lower than the outside area, with a few low-polarization patches radiating out. There could be a PD surrounding this source, but we cannot tell which one it is from the complicated polarization morphology.

From radio observations Gaume et al. (1995) suggest a south-north outflow from IRS1. The reflection nebulosities to the northwest and north are therefore likely to be the cavity wall of the blue-shifted outflow. Previous observations (Campbell, & Thompson 1984; Davis et al. 1998) show the redshifted lobe is spatially coincident with the blue-shifted one which extends to the northwest, suggesting that the outflow is seen nearly pole-on. This would explain why we do not clearly see the southern counterpart of the reflection nebulosity where the extinction is much larger.

From the methanol maser observation, Pestalozzi et al. (2004) suggested that there is a disk in the southeast-northwest direction. However, methanol masers can also be excited by high velocity gas. In light of our observation, it is also possible that the feature observed by Pestalozzi et al. represents one side of the cavity walls. Such an interpretation does not conflict to the scenario of a precessing outflow (Kraus et al. 2006).

IRAS 23033+5951: This is the most complicated region of the four. In the pseudocolor image (Fig. 1d, right panel), a conical nebulosity is seen, opening to the east. Several peaks are detected, but only the one marked by a plus (S1) is point-like (FWHM $\sim 0.3''$). To the east of S1, two other major peaks are detected. That they are not point-like and they have high polarizations suggests they are infrared reflection nebulosities (IRN). The northern one (IRN1) is mainly reflective; the polarization degrees are high ($\sim 20\%$) and the vectors are facing towards S1, indicating it is illuminated by S1. The polarization degrees are lower ($\sim 10\%$) in the southern one (IRN2), but the vectors also face to S1. The lower polarization could be caused either by a mixture of reflected light and self-radiation or by multiple illumination. To the northwest of S1, a faint reflection nebulosity is noticeable (IRN3), with relatively high polarization degrees ($\sim 30\%$). The polarization vectors suggest this nebulosity is illuminated by another probably deeply embedded protostar that is not visible in the NIR. Since the property of this source is beyond the scope of this paper, a detailed analysis of it will be presented later (Fang et al., in preparation).

Again, we see a low-polarization lane, which is more clearly seen in the polarization degree image (Fig 1d, left panel), running roughly south-north (p.a. $\sim 160^\circ$) and passing through the center of S1; the polarization vectors are generally aligned with the direction of the lane. As discussed above, this lane suggests the presence of a disk or a toroid. The length of this structure is about 6700 AU. The reflection nebulosities (IRN1 and IRN2) that are illuminated by S1, thus represent one direction of the outflow driven by S1. This result is quite intriguing since a bipolar outflow has been detected in the southeast-northwest (Kumar, Bachiller, & Davis 2002). Probably this outflow is driven by the deeply embedded protostar mentioned above. On the other hand, the outflow driven by S1 has its own manifestation. A shocked H_2 emission knot is found $4''$ west of S1 (Kumar, Bachiller, & Davis 2002), which is presumably excited by S1. It is interesting to note that the illuminating source, S1, is fainter than its illuminated reflection nebulosities in the K-band. A possible explanation is that the disk is seen edge-on so that the light directly from the central source is heavily

extincted while it can easily escape from the outflow cavity, then being reflected by the cavity walls. We note however, if only the extinction toward IRN1 and IRN2 is larger than that toward S1 ($A_{V(IRN1)} - A_{V(S1)} \geq 15$), an observed effect can be reproduced.

4. Implications and conclusions

There are several possible causes that make a low-polarization lane passing through the bright source. In addition to a flattened structure around the illuminating source, a magnetic field may also produce a similar morphology by dichroic extinction. We checked the polarization of point sources in our observed fields, and find no large-scale alignment of polarization vectors in the direction of PDs. Another possibility is that, when a nearly spherical envelop illuminated by a source inside and a much brighter source outside, the envelop will show a bipolar polarization structure. However, this happens when the source outside is hundreds to thousands of times brighter than the source inside, so that the photons from the two sources shining on the envelop are roughly equal. It is not possible in our case since our sources are brighter than $10^3 L_{\odot}$. It is also possible that a foreground filament which is just in front of the sources dilutes the polarization, but it is of very low probability and is in fact impossible to happen for all three targets. Therefore, taking the morphologies of the observed reflection nebulae into consideration, the most likely interpretation of the PDs here would be real disks or toroids. We note however, since the polarimetric observations do not give velocity information, it is not possible to distinguish between a Keplerian disk and a toroid structure. A confirmation of the conclusion have to await sensitive molecular line observations.

Some parameters of the sources are listed in Table 1. Of the four sources, three (S140 IRS1, S255 IRS1 and I23033) show evidence for the presence of a disk or toroid. All of them are deeply embedded ($A_V > 15$ for IRAS23033+5951, >20 for S255 IRS1 and >30 for S140 and NGC7538, Fig. 2a). They also show very large near infrared color excesses. Their near infrared colors suggest the evolutionary status could be comparable to low-mass Class I objects. Except for S255 IRS1, whose spectral type is still controversial (Heyer et al. 1989; Howard, Pipher, & Forrest 1997; Itoh et al. 2001), these sources are MYSOs with masses ranging between 10 to 30 solar masses according to their spectral types. A J vs J-H plot would also suggest a similar conclusion about spectral types of these objects (Fig. 2b).

Up to date, a dozen of MYSOs show evidence of the existence of disks (Cesaroni et al. 2006; Zinnecker & Yorke 2007). These candidate disks are found in various evolutionary status of their host objects, which are detected from (sub)millimeter wavelengths the NIR. However, the candidate disks happen around MYSOs with their luminosities less than $10^5 L_{\odot}$, typical of early B-type main-sequence stars (Cesaroni et al. 2006), suggesting that disks might be common occurrence for this kind of MYSOs; we still lack of evidence whether still higher-mass YSOs host circumstellar disks. Our observations add samples to this kind. And it is interesting to note that our most massive sample, NGC7538 IRS1 ($\sim 30 M_{\odot}$), does not show strong evidence of PD.

We have also shown that high-resolution polarimetric imaging can provide a sensitive tool to detect circumstellar disks around MYSOs, even if the disks are too faint to be detectable directly. Our future work will concentrate on searching for polarization disks around MYSOs of higher masses and different evolutionary status. We aim to set up a sample for future observations with higher resolution and sensitivity. This kind of work will give crucial hints to answer the question at what mass and evolutionary phase the disks around MYSOs are truncated.

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Table 1. Parameters of the sources

Name	D(kpc)	L(L _⊙)	Sp type	Size(AU) ¹	Ref. ²
S140 IRS1	0.9	5.00E+03	early B	2700	(1)
S255 IRS1	2.4	...	O,B0	5700	(2,3)
NGC 7538 IRS1	2.8	8.30E+04	O6	...	(4)
IRAS 23033+5951	3.5	2.51E+04	B0.5	6700	(5)

¹The projected length of the PD at adopted distance.

²Ref. Code 1. Lester et al. (1986); 2. Howard, Pipher, & Forrest (1997); 3. Itoh et al. (2001); 4. Kraus et al. (2006); 5. Williams, Fuller, & Sridharan (2005)

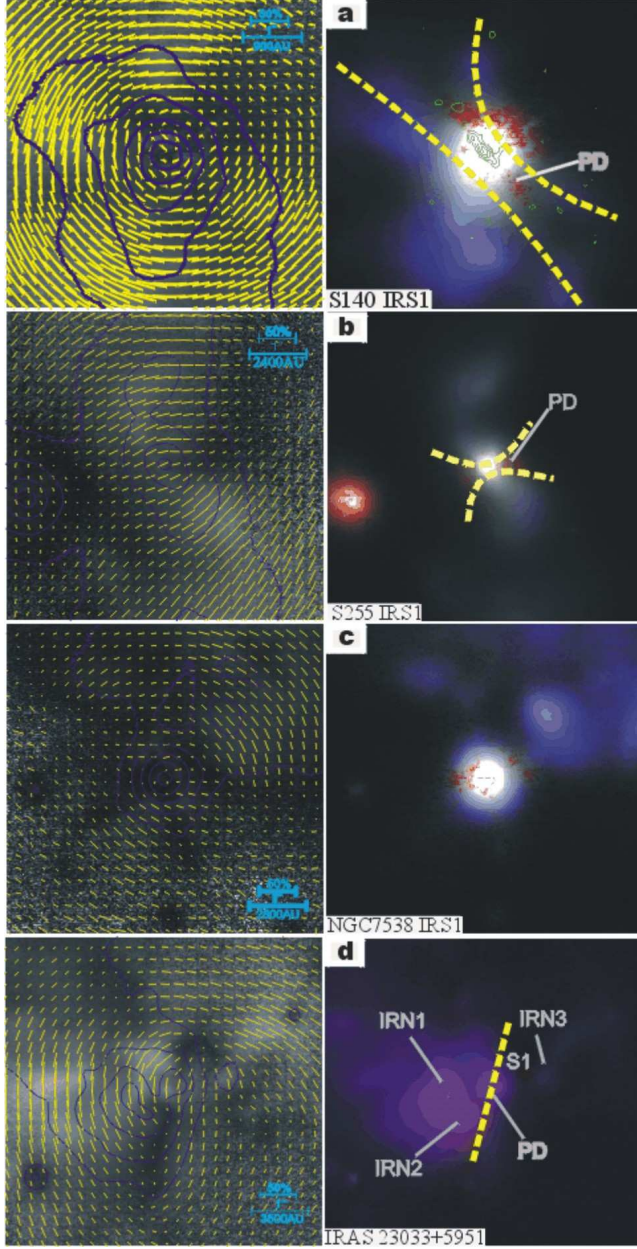


Fig. 1.— (left panels) Polarization degree images overlaid by polarization vectors (yellow dashes) and total intensity contour (blue curves). The angular and polarization scales are shown in the corners. The contours start from 10.93, 14.56, 11.34, 12.42 mag arcsec⁻², respectively, and decrease every 1.25 mag arcsec⁻². (right panels) Pseudocolor images composed of pure brightness images (red) and polarized brightness images (blue). A blue feature indicates the highly polarized nebulosity, which should be reflective. Red features are low polarization areas. The PD is indicated with double lines to delineate the edge of the disks (S140 IRS1 and S255 IRS2), or a single line to indicate the position (IRAS23033+5951). For S140 IRS1, The contours of 5 GHz continuum emission representing the ionized equatorial disk wind are superimposed (Hoare 2006). North is up and east is to the left.

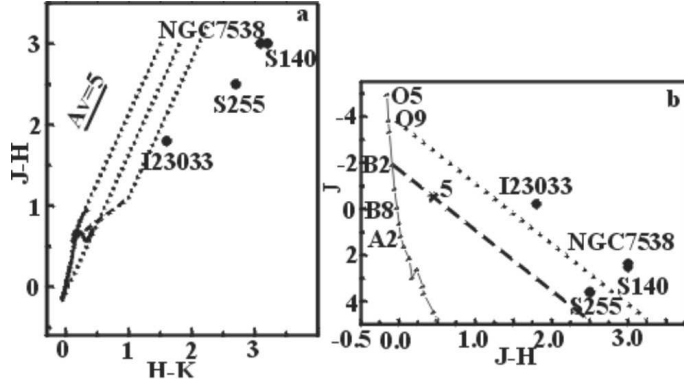


Fig. 2.— a. Near infrared color-color diagram. The JHK magnitudes were obtained from the 2MASS database. Solid curves show the loci of main-sequence dwarfs and giants. The dotted lines indicate the reddening bands of main-sequence and T-Tauri stars. b. J vs $J-H$ color-magnitude diagram of the sources. The solid curve indicates the zero-age main sequence stars with different spectral type. The dashed and dotted lines are drawn from B2 and O9 stars, parallel to the extinction vector, the scale of which is indicated by a cross on the dashed line.